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Electromagnetic effects in the Earth's ionosphere and magnetosphere caused by a cosmic body

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Abstract. The purpose of the present investigation is to study possible electromagnetic effects in the Earth's ionosphere and magnetosphere, which are caused by a cosmic body impact onto the atmosphere and by a cosmic body passage through the magnetosphere. An analysis of a cosmic body impact onto the atmosphere is carried out for a meteoroid with the kinetic energy of the order of 1 kt TNT. Such meteoroids are usually detected in the Earth's atmosphere several times a year. Variation of the electron density in the ionospheric plasma and excitation of plasma turbulence as a result of meteoroid impact events are shown to be associated with an appearance of the acoustic perturbation formed in the atmosphere due to the impact of the meteoroid. The evolution of the acoustic perturbation is studied. The electron density variation and parameters of ion–acoustic waves (and, in particular, ion–acoustic solitons), which are associated with the acoustic perturbation, are estimated. Variations of geomagnetic field strength caused by the meteoroid impact events and the rates of electron acceleration as a result of the interaction of the cosmic body with the Earth's atmosphere are evaluated. Most significant electromagnetic effects in the Earth's magnetosphere can be caused by a cosmic body embedded in a dust cloud. It is demonstrated that for an adequate description of the dust cloud with the magnetosphere the process of dust particle charging during the meteoroid passage should be taken into account. The presence of charged dust particles can result in the formation of a current system and (for sufficiently large density of dust particles, e.g. close to that related to the comet Shoemaker–Levy 9) in violation of the magnetic structure of the magnetosphere in the vicinity of the dust cloud. The possibility of auroral processes before the effective interaction of the cosmic body with the atmosphere, which are triggered by fast particles created due to Fermi acceleration process, is demonstrated. © 1997 Elsevier Science Ltd

Introduction

Some large meteoroids detected by satellites in the Earth's atmosphere (Tagliaferri *et al.*, 1994) have a kinetic energy of the order of 1 kt TNT[1] (Adushkin and Nemchinov, 1994). Such meteoroids are usually detected several times a year. In this article we shall concentrate most attention on such meteoroids. We note, however, that, although larger meteoroids (with kinetic energy of the order of 1 Mt TNT) occur more rarely in the atmosphere, their detection is possible rather often (one event per 10–20 yr). Some satellite measurements and those carried out on the Earth have shown the possibility of the appearance of oscillations in the magnetospheric and ionospheric plasmas over earthquake centres, explosive volcano eruptions, explosions in the atmosphere, etc. (Gokhberg *et al.*, 1982; Gohberg *et al.*, 1982; Sorokin and Fedorovitch, 1982; Galperin *et al.*, 1985). Plasma turbulence generated as a result of perturbations in the atmosphere (e.g. due to explosions) can be related to a change in the electron density variations in the ionosphere. This is confirmed, in particular, by analysis (Nagorsky, 1985) of consequences of the explosion carried out within the frames of the project MASSA (with the energy release of 260 t TNT). Thus one can expect (analogously to the case of usual explosions) that the energy release in the process of an impact of a meteoroid with high kinetic energy is accompanied by a change in the electron density in the ionosphere. This effect is, in particular, caused by the influence on the ionospheric plasma of an acoustic per-

[1]In the present paper we use the quantity kt TNT (kilotons TNT) to denote the kinetic energy of the meteoroid. 1 kt TNT corresponds to 4.2×10^{19} erg. This quantity is usually used in the context of nuclear explosions and is often used in the description of meteoroids (Adushkin and Nemchinov, 1994). A kinetic energy of 1 kt TNT for a meteoroid moving with speed 2×10^6 cm s^{-1} corresponds to a mass of 2.1×10^7 g of the meteoroid.

turbation formed in the process of the energy release. The electron density variations in the ionosphere can significantly influence radio wave propagation determining violation of phases, azimuth angles of the reflected waves, the characteristics of multiple-beam radio wave propagation, etc. Furthermore, the electron density variations and acoustic perturbation caused by the meteoroid impact can result in excitation of plasma turbulence in the ionosphere. Generation of plasma turbulence can lead to sufficiently effective electron acceleration due to their interaction with waves in a plasma. This, in turn, can result in excitation of atoms and molecules at altitudes exceeding 90 km in the region of the ionosphere magnetically related to the region of the energy release and, as a consequence, in glow of this region. If a cosmic body is embedded in a dust cloud (such as the comet Shoemaker-Levy 9 (Ip and Prangé, 1994; Dulk and Leblanc, 1995)) and moves through the magnetosphere of the Earth then the presence of the dust can also lead to electromagnetic effects in the ionosphere and magnetosphere.

Here, we estimate the effect of a change in the electron density in the ionosphere in the process of propagation of the acoustic perturbation and discuss possible difference between its manifestations for usual explosions and for meteoroid events. We discuss the possibility of excitation of ion–acoustic oscillations in the ionospheric plasma by the acoustic perturbation and possibility of an appearance of ion–acoustic solitons in the ionospheric plasma. We present the main parameters characterizing the ion–acoustic turbulence caused by the meteoroid events. We mention briefly the possible influence of the meteoroid events on the geomagnetic activity and give some estimates of the rates of electron acceleration as a result of the interaction of the cosmic body with the Earth's atmosphere. Finally, we consider effects caused by the presence of dust particles if the cosmic body moving through the Earth's magnetosphere is embedded in a dust cloud.

Acoustic wave

Variation of the electron density in the ionospheric plasma and excitation of plasma turbulence as a result of the meteoroid events are connected with an appearance of an acoustic perturbation in the atmosphere. We assume that the evolution of the acoustic perturbation formed in the atmosphere due to the impact of a meteoroid with the kinetic energy of the order of 1 kt TNT is the following: the acoustic shock perturbation is formed at the distance r_0 from the region of maximum energy release; the form of the perturbation profile can be approximated initially as a Glasstone pulse (Glasstone and Dolan, 1977); later the rarefied wave of this pulse is transformed to the second shock wave and the Glasstone pulse is converted to an N-like wave. Such evolution is analogous to that described by Nagorsky (1985) for the case of usual TNT explosions.

In analysing the evolution of the N-like wave, we suppose that the averaged wind is absent and neglect the temperature gradient as compared with pressure and density gradients, but, we take into account the dependence of the parameters of the problem on the temperature. Furthermore, for simplicity we use the approximation of short acoustic waves (Romanova, 1970) and assume Knudsen and Mach numbers to be small. Under these assumptions the evolution of the N-like wave is described by the Navier–Stokes set of equations where the gravitational effects should be taken into account, the equations of state, and statics equations. The expansion of the unknown functions in terms of Mach number in the above equations and consideration in the frame of reference moving together with the perturbation allow us to derive an evolution equation for the N-like wave which is analogous to Burgers equation (Nagorsky, 1985):

$$\frac{\partial u}{\partial r} - \frac{\gamma+1}{2}\frac{V_0}{\lambda_0}\left(\frac{r_0}{r}\right)^{n/2} \exp\left(\int_0^r \frac{r' \cos\varphi}{2rH}\,\mathrm{d}r'\right) u \frac{\partial u}{\partial r} = \frac{v_0}{2\lambda_0^2 c} \exp\left(\int_{r_0}^r \frac{r'\cos\varphi}{rH}\,\mathrm{d}r'\right)\frac{\partial^2 u}{\partial \tau^2} \quad (1)$$

where

$$u = \frac{V}{V_0}\left(\frac{r_0}{r}\right)^{n/2} \exp\left(-\int_0^r \frac{r'\cos\varphi}{2rH}\,\mathrm{d}r'\right)$$

$\gamma = c_p/c_v$, $n = 0$, 1, 2 characterizes the extent of perturbation divergence, r is the radial distance from the explosion centre, V_0 is the ratio of the amplitude of the oscillation speed of gas particles in the shock wave to the acoustic speed c at $r = r_0$, $V = V(r)$ is the compressional pulse profile, $\pi\lambda(r)$ is the length of the compressional pulse, $\lambda_0 = \lambda(r_0)$, φ is the zenith angle, v_0 is the damping coefficient, τ is the phase coordinate, $H = \kappa T/M_n g$ is the height of the homogeneous atmosphere, κ is the Boltzmann constant, T is the temperature, M_n is the atomic mass of the neutral, g is the gravity acceleration.

The solution to equation (1) shows that the evolution of the acoustic perturbation depends significantly on its geometry. The usual TNT explosions result in a three-dimensional "cupola-shaped" form of the acoustic perturbations ($n = 2$ in equation (1)). The geometry of the acoustic perturbation caused by the energy release in the process of the meteoroid impact is more complicated. This is because the meteoroid impact onto the atmosphere cannot be considered as a spheric explosion with a definite explosion centre. At least, at the first stage this process has cylindrical geometry ($n = 1$ in equation (1)). Unfortunately, the problem of formation and development of acoustic perturbation caused due to the meteoroid impact onto the atmosphere is not still completely solved. In particular, it is still not clear at which altitudes the form of the acoustic perturbation loses the cylindrical features and the perturbation can be considered as three-dimensional "cupola-shaped". This is connected with the fact that the characteristic size of the region of the meteoroid impact is the size of the homogeneous atmosphere, thus the cylindrical features in the form of the acoustic perturbations can be conserved over rather long period of time. We emphasize that an analysis (for cylindrical geometry of the energy release) of the generation and propagation characteristics of infrasonic pressure waves excited during meteoroid entry into the Earth's atmosphere has been carried out by ReVelle (1976). Unfortunately, the final solution to the problem of whether

the cylindrical features of the acoustic perturbation are conserved at the altitudes which are of interest from the viewpoint of study of electromagnetic effects has not yet been proposed. This problem requires further investigations.

In the following we use for estimates of the characteristics of the acoustic perturbation and of a change in electron density caused by this perturbation the results obtained under the assumption of a three-dimensional "cupola-shaped" form of the perturbation. This is related to the fact that we are interested in altitudes $h \sim 120$–200 km which significantly exceed the height H of the homogeneous atmosphere. One can expect that the influence of the cylindrical features in the geometry of the perturbation is not significant at these altitudes. Furthermore, estimates fulfilled for the cylindrical geometry of the acoustic perturbation show us that the cylindrical features in the geometry of the perturbation result in a weaker acoustic perturbation than the "cupola-shaped" one due to the usual explosion with the same energy release. Thus the use of the model of "cupola-shaped" geometry (generally speaking, with a reduced central energy) is legitimate for the description of the acoustic perturbation in our case, when we consider the altitudes $h \sim 120$–200 which are of interest from the viewpoint of the study of electromagnetic effects.

For energy releases of the order of 1 kt TNT we assume that $r_0 \sim 10^5$ cm, the ratio of the amplitude of the oscillation speed of gas particles in the shock wave to the acoustic speed c at $r = r_0$ is $V_0 \sim 5 \times 10^{-2}$, and the length of the compressional pulse (at $r = r_0$) is $\pi\lambda_0 \sim 10^4$ cm. These parameters are close to those used by Nagorsky (1985) to describe the usual explosion of energy release of 260 t TNT carried out on the Earth. Furthermore, these data allow us to find the values of the relative amplitude (A) and the length ($\pi\lambda$) of the compressional pulse at the altitudes of 120–150 km (where the maximum values of the wave amplitude are attained) which are of the order of the magnitudes of A and λ obtained (for the energy release of 1 kt TNT occurring at $h_0 \approx 40$ km) on the basis of formulae (Gubkin, 1958, 1961) which describe the dependence of the relative amplitude on the distance R from the energy release centre and on the energy released. Here we present Gubkin's formula for the case of an acoustic perturbation of three-dimensional ("cupola-shaped") geometry and for vertical propagation of the perturbation:

$$A \approx \frac{\Delta p}{p} \approx \frac{0.135E^{1/3}}{R\sqrt{2.68+0.17R-\ln E^{1/3}}} \exp\left\{\frac{h_0}{3H}+\frac{R}{2H}\right\}$$

where E is the energy released in the meteoroid impact event expressed in units of kt TNT; R, h_0, and H are calculated in units of km; p is the pressure at the altitude $h_0 + R$; and Δp is the pressure variation in the wave. The presence of the maximum values of the wave amplitude at altitudes of about 120–150 km is connected with the fact that the main energy absorption of the acoustic perturbation is related to the non-linear absorption for the altitudes below 120–150 km. At the altitudes of 120–180 km the decrease in perturbation amplitude is also related to the increase of the acoustic velocity with the altitude. Above 170–180 km the main contribution to the amplitude decrease is made by the viscosity. The length of the compressional pulse increases with altitude so that at an altitude of about 200 km the length of the pulse is two orders of magnitude larger than at the surface $r = r_0$. For $r_0 \sim 10^5$ cm, $V_0 \sim 5 \times 10^{-2}$, $\pi\lambda_0 \sim 10^4$ cm, and $h_0 \approx 40$ km we find that at the altitude $h \sim 150$ km $A \sim 2 \times 10^{-1}$, $\pi\lambda \sim 5 \times 10^5$ cm.

We emphasize that the above results can be influenced by the presence of the wake behind the meteoroid. The gas in this wake has the characteristics different from those of the ambient gas. Accordingly, the properties of the acoustic perturbation propagating inside the wake are different from those in the ambient gas.

Electron density variation

Estimate the electron density perturbation in the ionosphere caused by the meteoroid events. We present the electron density in the form $n_e(r,t) = n_0(h)[1 + n'_e(r,t)]$, where n_0 is an unperturbed value of the electron density, $n'_e(r,t)$ is the electron density deviation from the unperturbed state caused by the acoustic perturbation. We shall consider separately three regions:

- the region E of the ionosphere where $\omega_{Bi} \ll \nu_{in}$;
- the lower part of the region EF where $\omega_{Bi} \sim \nu_{in}$, $n_0 \sim \text{const}$;
- the upper part of the region EF and the region F of the ionosphere where $\omega_{Bi} \gg \nu_{in}$.

Here ω_{Bi} is the ion gyrofrequency, ν_{in} is the frequency of binary collisions between ions and neutral particles.

Under the assumption that the electron density distribution in the region E is given by the expression $n_0 \approx n_m \exp[-(h-h_m)^2/\Delta h^2]$ (where n_m is the maximum value of the electron density in the region E, Δh is the characteristic width of this region) the electron density variation in the region E is (Gokhberg *et al.*, 1982)

$$n'_e = V - 2A\frac{h-h_m}{\Delta h^2}\lambda\psi\cos\varphi \tag{2}$$

where

$$\psi = \begin{cases}(\tau-\tau^2/2)/\pi & \text{if } 0<\tau\le\pi \\ \Delta\ln\cosh(\tau/\Delta)+\tau & \text{if } \tau\sim 0.\end{cases} \tag{3}$$

In the lower part of the region EF we have (Gershman, 1974)

$$n'_e = V\frac{\nu_{in}^2}{\omega_{Bi}^2+\nu_{in}^2}\left(1+\frac{\omega_{Bi}^2}{\nu_{in}^2}\cos^2\theta\right) \tag{4}$$

where θ is the angle between the wave vector $\mathbf{k}$ of the acoustic perturbation and the direction of the geomagnetic field.

In the region F of the ionosphere the electron density perturbation in the frame of reference created by the axes Ox_1, Oy_1, Oz_1 with the axis Oz_1 in the direction parallel to the geomagnetic field is described by the expression (Nagorsky, 1985)

$$n'_e = \frac{1}{n_0}\int_0^t \int_{-\infty}^{\infty} \frac{d(n_0 v_\parallel)}{dz_1} G(z_1, z'_1, t-t')\, dt'\, dz'_1 \quad (5)$$

where $G(z_1,z'_1,t-t')$ is the Green function given by

$$G(z_1,z'_1,t-t') = \exp\left[-\frac{z_1-z'_1}{4D(t-t')}\right] \Big/ \sqrt{4D(t-t')} \quad (6)$$

the subscript $\parallel$ denotes the vector component parallel to the geomagnetic field, $D = \kappa(T_e+T_i)/M_i v_{in}$ is the coefficient of the ambipolar diffusion, M_i is the ion mass, $T_{e(i)}$ is the electron (ion) temperature. Equation (5) is obtained under the assumption that the ionosphere is a layer with the width L (so that $L \gg 2\pi/k_\parallel$) and that the boundaries of the layer do not influence the deviation of the electron density from the steady-state values. This enables to set the boundary condition $n'_e = 0$ at infinity. The Fourier transformation for the values $v_\parallel$ and n'_e gives the following result for the Fourier component of the electron density variation

$$n'_e = -V\frac{\cos^2\theta}{1+q^2}\left\{1 - i\alpha - q\left[\alpha\left(1+2\frac{1-q^2}{1+q^2}\right) + i\left(1+\alpha\frac{4q}{1+q^2}\right)\right]\right\} \quad (7)$$

where $\alpha = (n_{02}-n_{01})\pi/n_0 k_\parallel L$, $n_{01(2)}$ is the unperturbed value of the electron density at the lower (upper) boundary of the ionospheric layer, $q = \mathbf{k}^2\kappa(T_e+T_i)/M_i \omega v_{in}$.

Thus the electron density variation is proportional to the amplitude A of the acoustic perturbation in all three regions considered of the ionosphere. For the meteoroid impact resulting in the acoustic perturbation which is characterized by $n = 2$, $r_0 \sim 10^5$ cm, $V_0 \sim 5\times10^{-2}$, and $\pi\lambda_0 \sim 10^4$ cm the maximum values of the electron density variations n'_e are attained at the altitudes $h \approx 120$–150 km and are of the order of 0.1. If the cylindrical features in the geometry of the acoustic perturbation are significant up to the altitudes $h \sim 150$–200 km (so that we can use the estimate $n = 1$, $r_0 \sim 10^2$–10^3 cm, $\pi\lambda_0 \le 10^2$ cm, and $V_0 \sim 5\times10^{-2}$) then the maximum value of the variation of the electron density is smaller: $n'_e \ll 0.1$.

We emphasize that the above estimates of the electron density variation imply that the regions E and F of the ionosphere are not stratified. However, an appearance of different layers in these regions can lead to significant changes in both the form and the amplitude of the acoustic perturbation. Furthermore, the model used implies that the acoustic perturbation propagates in an atmosphere gas consisting of neutral particles. However, in the ionosphere the *usual* acoustic perturbation can result in the generation of ion–acoustic waves and other plasma modes and through this it can be modified. Moreover the plasma modes can, in turn, influence the acoustic perturbation. All these effects can modify the above estimates.

Oscillations in plasma

We now discuss the possible appearance of oscillations in the ionospheric plasma due to the effect of the acoustic perturbation created in the process of impact of the meteoroid. Here we restrict ourselves to the case when the effect of the energy release in this process can be described in terms of an explosion with $n = 2$, $r_0 \sim 10^5$ cm, $V_0 \sim 5\times10^{-2}$, and $\pi\lambda \sim 10^4$ cm, i.e. when we can neglect the cylindrical features in the form of the acoustic perturbation.

As has been shown above the acoustic perturbation created in the process of impact of the meteoroid can result in an appearance of density variations $n'_e \sim 0.1$. This effect is connected with the motion of charged particles arising due to collisions of neutral particles moved by the acoustic perturbation with the charged particles. The acoustic perturbation can, in particular, be converted to the ion–acoustic mode. This occurs at altitudes of 150–200 km (the so-called altitudes of the acoustic zone) where the frequency of inelastic collisions exceeds that of elastic collisions (Alebastrov *et al.*, 1985). The time at which the acoustic perturbation reaches these altitudes is of the order of 5×10^2 s. Since in the process of the mode conversion the frequency ω is assumed to be constant, we can estimate the frequency of the ion–acoustic mode and the component parallel to the geomagnetic field of its wave vector. Indeed, the characteristic value of the length of the acoustic pulse at the altitude $h \sim 150$ km is $\pi\lambda \sim 5\times10^5$ cm, the acoustic velocity is $c = \sqrt{\gamma\kappa T/M_n} \sim 5\times10^4$ cm s^{-1}, the ion-sound velocity is $v_{is} \equiv \sqrt{\kappa T_e/M_i} \sim 5\times10^4$ cm s^{-1} (we suppose that $\gamma = 5/3$, $T \sim 600$ K; the electron temperature $T_e \sim 800$ K; the constituents of the plasma at this altitude are electrons, the ions NO^+ and O_2^+, and neutral particles, the main neutral components are N_2, O, and O_2 (Mishin *et al.*, 1989)). Thus the characteristic value of the wave vector length of the acoustic perturbation is $k_a \sim 2\pi/\lambda \approx 4\times10^{-5}$ cm^{-1} and the characteristic frequency is $\omega = k_a c \sim 1$ s^{-1}. This frequency is significantly less than the ion gyrofrequency at the altitudes considered: $\omega_{Bi} \sim 10^2$ s^{-1}. Furthermore, the frequency ω is much less than the frequency of collisions between electrons and other plasma particles. The latter is $v_e \sim v_{en} \sim v_{in} \sim 10^3$ s^{-1} at $h \sim 150$ km (Mishin *et al.*, 1989). Thus the acoustic perturbation is converted to the magnetized ion–acoustic mode in a collisional plasma, i.e. its dispersion law is $\omega = k_\parallel c_s$, where c_s is the ion sound speed for such a plasma which differs, in general, from v_{is} (see, e.g. Vladimirov *et al.*, 1995). We note that

$$|\omega| \gg 3\frac{M_e}{M_i} v_e \quad (8)$$

where M_e is the electron mass. The characteristic frequency $3v_e M_e/M_i$ corresponds to the inverse time of the electron and ion temperature equalization. Consequently, we can assume that in the wave the relationship between the electron (T_e) and ion (T_i) temperatures is conserved, i.e. since at $h \sim 150$ km $T_e \sim T_i$, we can consider that the latter relation remains valid in the wave. In this case we have (Vladimirov *et al.*, 1995, p. 334)

$$c_s = v_{Te}\left[\frac{M_e}{M_i}\left(1+\frac{5}{3}\frac{T_i}{T_e}\right)\right]^{1/2} \quad (9)$$

where $v_{Te} = \sqrt{\kappa T_e/M_e}$ is the electron thermal velocity. Thus the component parallel to the geomagnetic field of

the wave vector $\mathbf{k}_{is}$ of the ion–acoustic wave is of the order of the characteristic length of the wave vector $\mathbf{k}_a$ of the acoustic perturbation: $|k_{is\parallel}| \sim |\mathbf{k}_a| \approx 4\times10^{-5}\,\mathrm{cm}^{-1}$.

The collisional damping rate for these waves is (Vladimirov *et al.*, 1995) $\gamma_s = \gamma^{(e)}+\gamma^{(i)}$, where

$$\gamma^{(e)} \approx -0.41\frac{M_e}{M_i}\nu_e,\ \gamma^{(i)} \approx = -\frac{1.92+0.64(T_e/T_i)}{(5/3)+(T_e/T_i)}\frac{k_\parallel^2 v_{Ti}^2}{\nu_i}. \tag{10}$$

From these formulae we can estimate the characteristic time of existence of the ion–acoustic wave: $\tau_{is}\sim|\gamma_s|^{-1}$. Assuming that $M_i = M_{O_2^+}$, $\nu_e\sim10^3\,\mathrm{s}^{-1}$, and estimating $\gamma_s = \gamma^{(e)}$, we find $\tau_{is}\sim200$ s. This time is significantly longer than the time of the acoustic perturbation passage through the layer with dimension of the order of $\pi\lambda$ (the latter time is $t\sim\pi\lambda/v_s\sim10$ s). Thus the amplitude of the ion–acoustic wave excited by the acoustic perturbation increases with time.

Above we have determined some characteristic values of the ion–acoustic wave. Generally speaking, the spectrum of the ion–acoustic perturbation in **k**-space is sufficiently wide. Indeed, $\pi\lambda$ is the length of the acoustic pulse. Therefore the acoustic perturbation contains different Fourier components (not only with $k\sim2\pi/\lambda$). For the flat profile of the acoustic perturbation in the region $r_1\le r\le r_2$ (where $r_2-r_1 = \pi\lambda$) and zero perturbation outside this region, the Fourier component corresponding to the wave vector **k** varies as $(\exp(-i\pi\lambda k)-1)/k$. The main contribution to the Fourier component (determining the tendency of its decrease for large k) is made by the factor $1/k$. This means that not only the waves with $\omega\sim1\,\mathrm{s}^{-1}$ but also with larger $\omega\sim kv_s$ can appear in the spectrum of the ion–acoustic oscillations.

We now discuss the possibility of an appearance of ion–acoustic solitons in the ionospheric plasma. In accordance with the results of Alebastrov *et al.* (1985) at the altitudes of the order of 200 km the formation of ion acoustic solitons is possible as a result of explosions with the energy release of about several kt TNT. In our case, the electron density perturbation caused by the acoustic perturbation is significant: $n_e'\sim0.1$. This implies the possibility of the appearance of strongly non-linear ion–acoustic waves. Using the formula describing a (small-amplitude) ion–acoustic soliton propagating in the collisionless plasma (see, e.g. Popel *et al.*, 1995) we find the soliton width $\Delta x\sim10$–100 cm for the Debye length in the ionospheric plasma $r_{De}\sim1$–10 cm.

Let us estimate the electron density variation caused by an ion–acoustic soliton for an arbitrary energy release due to meteoroid event. We use the Boltzmann distribution for the electron density and assume that the α_0-part of the energy of the acoustic perturbation is transformed to the ion–acoustic wave. For the ionospheric parameters at the altitude of about 200 km: $n_e\sim3\times10^5\,\mathrm{cm}^{-3}$, $T_e\sim1.5\times10^3$ K; the energy of the cosmic body $E_k\approx1$ kt TNT, $\alpha_0\approx3\times10^{-4}$, we obtain $n_e'\sim1$ (the magnitude of α_0 is chosen so that one can obtain the magnitude $n_e'\sim1$ observed as a result of an explosion described by Alebastrov *et al.* (1985)). Thus for the kinetic energies of the cosmic body exceeding 1 kt TNT the variations of the electron density perturbations can be significant and reach their maximum values $n_e'\sim1$. Such strong perturbations can, in particular, influence radio wave propagation.

Above we have considered excitation of the electrostatic ion–acoustic oscillations in the ionospheric plasma accompanied by a variation of electron density. The second important effect is related to variations of geomagnetic field strength. These variations can, in particular, be created by Alfvén waves excited as a result of strong actions on the Earth's surface or on the atmosphere (see, e.g. Galperin *et al.*, 1985). The significant part of the energy of the Alfvén wave is contained in its magnetic field. Significant magnetic field variations $\delta B\sim B_0$ due to the Alfvén wave excitation are possible only for cosmic bodies with very large kinetic energy (of the order of 100 Mt TNT).

Excitation in the ionospheric plasma of sufficiently intense oscillations caused by meteoroid events results in the possibility of resonant acceleration of plasma particles. To describe processes similar to those leading to auroral events one has to explain the generation of fast electrons with energies from hundreds of eV to tens of keV. Consequently, the problem of interest is to determine the rate of generation of electrons with energies of the order of 1 keV.

The process of resonant acceleration is described by the quasilinear equation (see, e.g. Tsytovich, 1989). For the case of the ion–acoustic waves the number of resonant (with these waves) *fast* electrons ($v\gg v_{Te}$, where **v** is the electron speed) is negligibly small. Therefore, the process of the radiative–resonant acceleration (Tsytovich, 1989) can be important.

Using the quasilinear equation we find that the rate ε^{res} of energy increase of electrons *resonant* with the waves is

$$\frac{\partial\varepsilon^{res}}{\partial t}\propto\omega_{pe}T_e\frac{v_{Te}}{v}\frac{W}{n_0T_e} \tag{11}$$

where ω_{pe} is the electron plasma frequency, W is the energy density of the oscillations in the plasma. The rate of energy increase of *fast* ($v\gg v_{Te}$) electrons due to the process of the radiative–resonant interactions takes the form (Tsytovich, 1989)

$$\frac{\partial\varepsilon^{fast}}{\partial t}\approx1.45\times10^{-3}\frac{\partial\varepsilon^{res}}{\partial t}. \tag{12}$$

The last estimate allows us to determine the rate of increase of the number of fast electrons (let us remind that we are interested in consideration of particles with the energy ~1 keV):

$$\frac{\partial n_e^{fast}}{\partial t}\sim n_0\frac{1}{\varepsilon^{fast}}\frac{\partial\varepsilon^{fast}}{\partial t}. \tag{13}$$

The estimate for the data $R\sim200$ km, $n_0\sim3\times10^5\,\mathrm{cm}^{-3}$, $T_e\sim1.5\times10^3$ K, $E_k\sim1$ kt TNT, $\alpha_0\sim0.3\times10^{-4}$), and $\varepsilon^{fast}\sim1$ keV gives $\partial n_e^{fast}/\partial t\sim10^{-2}n_0\,\mathrm{s}^{-1}$. This magnitude is sufficiently large (we recall that the time of existence of the ion–acoustic oscillations is several minutes, i.e. most (or at least a significant part) of the electrons interacting with the ion–acoustic oscillations can be accelerated up to energies of the order of 1 keV). Thus the process of electron acceleration as a result of the interaction of a cosmic body with the atmosphere can be important (it

can result in excitation of atoms and molecules of the ionosphere) and should be taken into account.

Effects caused by the presence of dust particles

If a cosmic body is embedded in a dust cloud (as with the comet Shoemaker–Levy 9) and moves through the magnetosphere of the Earth then this can lead to additional electromagnetic effects which are caused by the presence of dust particles. Interaction of the magnetospheric plasma with particles of the dust cloud results in charging of the latter. The equilibrium charge of a dust particle is established in the process of equalization of electron and ion currents on this particle, and (for thermal equilibrium distributions) it can be determined from the equation (Tsytovich and Havnes, 1993)

$$\frac{\omega_{pe}^2}{v_{Te}}\exp(-z) = \frac{\omega_{pi}^2}{v_{Ti}}(t+z) \tag{14}$$

where

$$t \equiv \frac{T_i}{T_e}, \quad z \equiv \frac{Z_d e^2}{aT_e} \tag{15}$$

a is the characteristic size of the dust particle, $-e$ is the electron charge, $-Z_d e$ is the dust particle charge. In hydrogen plasma, for $t = 1$ we have $z = 2.5$. If $a \sim 1\ \mu$m and $T_e \sim 1$ keV (that is inherent in the plasma layer and the ring current of the magnetosphere) then Z_d is of the order of 10^6.

The presence of a dust cloud in the Earth's magnetosphere can result in the possibility of formation of a global current system. The effect of its formation is due to the differential motion between the negatively charged dust particles and the corotating (with the Earth) plasma. The dust grain moves across the magnetic field whereas the magnetospheric thermal ions must gyrate along the magnetic field lines and hence are trapped in corotation with the Earth. The relative motion of these two charge carriers in the azimuthal direction will lead to a current. The dust current flowing across the magnetic field lines will be mapped from the dust cloud to the Earth's ionosphere via a system of field-aligned currents. The situation is analogous to that predicted by Ip and Prangé (1994) for the case of interaction of the comet Shoemaker–Levy 9 with the Jovian magnetosphere and ionosphere and similar to the planetary dust ring/cloud current systems considered previously by several authors (see, e.g. Ip and Mendis, 1983; Goertz and Morfill, 1983; Mendis *et al.*, 1984). The evaluation of such a current for the total number of dust grains in a dust cloud ($N \approx 3 \times 10^{20}$) and the radius of the dust cloud (10^9 cm), which are close to those related to the comet Shoemaker–Levy 9 (Ip and Prangé, 1994), and for a space body velocity of 2×10^6 cm s^{-1} at a distance of about 10 Earth's radii from the Earth's surface gives us the value of the current of the order of 10^5 A. Thus a sufficiently intense current appears. The magnetic field created by this current at the boundary of the dust cloud is $B \sim 4 \times 10^{-4}$ G. This magnitude exceeds the magnetic field in the plasma layer of the magnetosphere ($B \sim (1\text{–}2) \times 10^{-4}$ G). Thus in the vicinity of the dust cloud the magnetic structure of the magnetosphere can be violated. Furthermore, the width of the current flow can be comparable with the size of the dust cloud (Ip and Prangé, 1994). In this case the electrodynamical coupling of currents flowing in different directions is possible. Electrodynamical coupling of intense currents normally triggers characteristic auroral processes, including parallel electric fields, energetic particle acceleration along field lines and precipitation, together with the generation of radio waves. These processes would lead to the detection of an enhanced level of auroral UV and radio emission.

If the dust particles have magnetic moment (e.g. if they are fragments of broken siderolite) and one can suppose that they are distributed in space randomly then particle acceleration based on the mechanism Fermi is possible (see, e.g. Tsytovich, 1989). The rate of the energy increase of particle is

$$\langle \mathrm{d}\varepsilon/\mathrm{d}t \rangle = 4\varepsilon v u^2/Lc_0^2 \tag{16}$$

where ε is the energy of the particle, v is its velocity, u is the velocity of dust grains (i.e. the velocity of the cosmic body embedded in the dust cloud), L is the mean distance between the dust grains, c_0 is the velocity of light. Using the data of Ip and Prangé (1994) related to the comet Shoemaker–Levy 9: the number of dust grains $N \sim 3 \times 10^{20}$ and the size of the dust cloud $r \sim 10^9$ cm, we find that the mean distance between the dust particles is $L \sim (3N/4\pi r^3)^{-1/3} \sim 2 \times 10^2$ cm. For $u \sim 2 \times 10^6$ cm s^{-1} we find from equation (16) that electron can acquire a velocity of the order of the velocity of light c_0 in a time of the order of 1 s. This means the possibility of creation of fast particles which can trigger auroral processes before the effective interaction of the cosmic body with the atmosphere (approximately 1 h before).

Summary

In summary, the analysis of the evolution of an acoustic perturbation formed in the atmosphere due to an impact of a meteoroid with a kinetic energy of the order of 1 kt TNT is presented. If in the ionosphere one can neglect the cylindrical features in the form of the acoustic perturbation then the characteristics of the acoustic perturbation in the ionospheric plasma are close to those of the perturbation formed due to a usual explosion with the energy release coincident with that in the meteoroid event. For the estimates we have used experimental data obtained for TNT explosions on the Earth (experiments MASSA). In these cases an increase of geomagnetic activity was detected by satellites. Conservation of the cylindrical features in the geometry of the acoustic perturbation in the ionosphere results in a different action on the ionosphere of a meteoroid impact and of the usual explosion of the same energy release.

We have discussed the possibility of excitation of ion–acoustic oscillations in the ionospheric plasma by the acoustic perturbation and the possibility of an appearance of ion–acoustic solitons in the ionospheric plasma. The process of conversion of the acoustic perturbation to the ion–acoustic mode occurs at the altitudes of 150–200 km. The time at which the acoustic perturbation reaches these altitudes is of the order of 5×10^2 s. The characteristic

frequency of the ion–acoustic oscillations is of the order of $1\ s^{-1}$. However oscillations with higher frequencies are also present in the plasma. We have presented the dispersion law of the ion–acoustic oscillations and their damping rate. The time of existence of these oscillations in the ionospheric plasma is several hundreds of seconds. High values of the electron density variation indicate the possibility of an appearance of ion–acoustic solitons as a result of the meteoroid events. For the relative electron density variation in the soliton of about 0.1 its width can reach values of about 100 cm. We have estimated the relative electron density variation for arbitrary energy release due to meteoroid event. For kinetic energies of cosmic bodies exceeding 1 kt TNT the relative electron density variation can reach its maximum values (of the order of unity). Such strong perturbations can, in particular, influence radio wave propagation. We have estimated variations of geomagnetic field strength caused by the meteoroid events and have given some estimates of the rates of electron acceleration as a result of the interaction of the cosmic body with the Earth's atmosphere. Most (or at least a significant part) of electrons interacting with the ion–acoustic oscillations can be accelerated up to the energies of the order of 1 keV.

Electromagnetic effects in the Earth's magnetosphere caused by a cosmic body embedded in a dust cloud have been also considered. The process of dust particle charging during the meteoroid passage has been taken into account. The charge gained by dust particles has been found. The presence of charged dust particles is shown to result in the formation of a current system and (for a sufficiently large concentration of dust particles) in violation of the magnetic structure of the magnetosphere in the vicinity of the dust cloud. The case of dust particles with non-zero magnetic moment has also been considered. In this case the particle acceleration based on the Fermi mechanism can be important. The possibility of auroral processes triggered in this case before the effective interaction of the cosmic body with the atmosphere has been shown.

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